



Profiling the novel plant-based meat alternative category: Consumer affective and sensory response in the context of perceived similarity to meat

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ABSTRACT

Plant-based meat alternatives (PBMA) are increasingly popular and may contribute towards reduction of negative environmental impacts associated with the meat industry. Inferior sensory characteristics of PBMA, compared to conventional meat products, remain a barrier for uptake of these products. This study aimed to profile a wide range of PBMA for perceived similarity to meat, consumer liking, emotional response and sensory experience, and to determine consumer drivers of liking for this product category. Twenty-one PBMA, spanning a broad range of product types (burger patties, sausages, meatball alternatives, chicken/beef pieces, bacon alternative, turkey roast alternative) and main protein ingredients (extruded plant proteins, tofu, or legumes/vegetables) representative of PBMA available to Aotearoa New Zealand consumers, were tasted and evaluated by 140 Aotearoa New Zealand residents. Samples ranged widely in their perceived similarity to meat (median value range: 1.0–4.0 on a 5-point-scale) and overall liking ratings (mean \pm SD, range: 35.1 ± 1.2 – 77.7 ± 17.4 on a 100-point hedonic scale). Overall liking ratings were driven mostly by liking for flavour, followed by texture, and less so by appearance. Sensorially, sample differentiation was mostly associated with variation in meat-related flavours and textures, or vegetable-related attributes. Notably meat flavour was the main driver of liking, and a very strong relationship ($r = 0.92$) was observed between perceived similarity to meat and overall sample liking ratings. Meat-like samples were also associated with positive emotional terms, whereas samples made from wholefoods were associated with negative emotional terms. Textural terms ('gluey/slimy', 'pasty/doughy') associated with wholefood products were also negative drivers for liking, and should be avoided in future PBMA products. In conclusion, the general population maintains a strong preference for PBMA that are similar to meat, validating ongoing efforts to improve the meat-like properties of new and emerging products. PBMA made from wholefoods require extensive product development to achieve consumer satisfaction across the category.

1. Introduction

With an intensified focus on sustainable food systems that support enhanced environmental sustainability and human health, plant-based meat diets have received increased interest (Willett et al., 2019). Adoption of plant-based diets may contribute to reduction of negative environmental impacts associated with the meat industry, such as water

use and greenhouse gas emissions. Furthermore, plant-based diets have been recommended to enhance personal health, whilst simultaneously encouraging a shift towards a food system that contributes towards global food security (Willett et al., 2019).

Plant-based meat alternatives (PBMA) have been developed to replace animal protein with plant-based protein in a convenient way, catering particularly to those who intend to reduce their meat

Abbreviations: AIC, Akaike Information Criterion; A-NZ, Aotearoa New Zealand; CATA, Check all that apply; PBMA, Plant-based meat alternative; GLM, generalised linear model; PC, Principal component; PCA, Principal component analyses; R^2 , R-squared.

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consumption (Tso et al., 2021). PBMA's can be divided into two categories: those aiming to imitate the sensory profile of a conventional meat product, often made from extruded plant proteins (soy, pea, wheat) as the main protein source, and other vegetable-based products which do not aim to imitate conventional meat and include wholefood products as the main protein ingredient, such as legumes or quinoa (Tso et al., 2021). Although sales of PBMA's have increased over recent years, overall uptake is still low, only accounting for 1.4 % market share of the United States of America's meat industry in 2021 (Good Food Institute, 2022), slightly decreasing to 1.3 % in 2022 (Good Food Institute, 2023).

Sensory characteristics remain a barrier for uptake of PBMA's (Caputo et al., 2022; Ettinger et al., 2022; Godschalk-Broers et al., 2022; Hoek et al., 2011). The use of pulse-derived ingredients commonly used in PBMA's, either as a whole seed, or processed into pulse proteins, frequently results in perceptions of bitterness, musty/dusty, beany and astringency flavours (Chigwedere et al., 2022). Notably, taste was reported as a barrier for trying PBMA's in 51 % of consumers, and 46 % of consumers reported taste to be a reason why they did not repurchase a product (Good Food Institute, 2023).

Sensory evaluation has shown that conventional meat products are generally preferred over PBMA's by consumers who do not avoid meat products in their diet (Cordelle et al., 2022; Ettinger et al., 2022; Godschalk-Broers et al., 2022; Grasso et al., 2022; Neville et al., 2017). Perhaps as a result, meat-flavour has been reported repeatedly as a major driver of liking (Barker and McSweeney, 2022; Godschalk-Broers et al., 2022; Neville et al., 2017; Sogari et al., 2023) and willingness to buy a product (Baune et al., 2023) in sensory evaluations of PBMA's.

To generate a deeper understanding of affective responses towards PBMA's, emotional response may be able to discriminate products that would not be discriminated through ratings of liking alone (Meiselman et al., 2022; Ng et al., 2013). When compared to conventional meat, Schouteten et al. (2016) found plant-based burger patties had higher frequency counts for negative emotions and lower frequency counts for positive emotions and found the most frequent emotions associated with PBMA's to be 'discontented', 'disappointed', 'dissatisfied' and 'distrust'. During the development of an emotions lexicon specifically for PBMA's, consumption of these products was found to evoke emotions such as suspicion, deceit, anxiety, uncertainty and amazement – emotions not included in the EsSense Profile commonly used to measure consumer emotional response to foods (Orr et al., 2023). These additional emotions likely reflect those experienced when a consumer is presented with a product that resembles, but is not actually, conventional meat (Orr et al., 2023).

Considering the rapid increase in the development and availability of PBMA's, sensory evaluation of the wider PBMA category is, in reality, relatively scarce, and limitations exist in studies published to date. Most studies have been designed from a product development perspective or aim to analyse flavour compounds in which affect towards the product is not measured (De Angelis et al., 2020; Dreher et al., 2021; Hernandez et al., 2023; Kaczmarek et al., 2021; Kamani et al., 2019; Yuliarti et al., 2021), or involve sensory characterisation performed only by a trained panel (De Angelis et al., 2020; Hernandez et al., 2023; Kaczmarek et al., 2021; Kamani et al., 2019) or by low numbers of consumers (around 40) (Dreher et al., 2021; Yuliarti et al., 2021). Notably, studies focused on sensory evaluation also mostly include only one product type (e.g. all burger patties) (Ettinger et al., 2022; Grasso et al., 2022; Schouteten et al., 2016; Taylor et al., 2020), often have only six or less samples per study (Cordelle et al., 2022; Grasso et al., 2022; Hernandez et al., 2023; Pointke et al., 2022; Schouteten et al., 2016; Taylor et al., 2020) and, with some exceptions (Moussaoui et al., 2023; Schouteten et al., 2016), only measure liking and sensory characteristics and do not include emotional response towards PBMA's (Cordelle et al., 2022; Ettinger et al., 2022; Grasso et al., 2022; Hernandez et al., 2023; Pointke et al., 2022; Taylor et al., 2020). Most studies have used burger patties as the stimuli, with only very few studies measuring affect and/or sensory attributes of different product categories, although some included plant-based

chicken alternatives (Ettinger et al., 2022; Godschalk-Broers et al., 2022), sausages (Yuan et al., 2022), or salami (Pointke et al., 2022). Although perceptions of meat-like and vegetable-based meat alternatives have been compared in online surveys (Hartmann et al., 2022; Michel et al., 2021a), sensory evaluations of PBMA's mostly include samples that aim to imitate conventional meat. To generate deeper insights into sensory drivers of (dis)liking in this product category, a range of product types, that varies widely in sensory characteristics, and includes both products that imitate meat and products that do not, is required.

Consequently, the objectives of the study were firstly, to identify a range of commercially available products representative of a complete PBMA market available to consumers (Aotearoa New Zealand (A-NZ)). Secondly, to characterise variation in the PBMA category in terms of perceived similarity to meat, consumer acceptance, emotional response and sensory experience. Lastly, to determine the relationships between sensory attributes and consumer acceptance and perceived similarity to meat, to determine drivers of liking for the PBMA category.

2. Methods

This study was evaluated via the Massey Human Ethics Committee process and was judged to be low risk (Application ID 4000025647).

2.1. Participants












Participants (n = 140) were recruited using the Food Experience and Sensory Testing (Feast) consumer database. The following inclusion criteria were assessed through a screening survey: i) aged between 25 and 55 years, ii) able to communicate effectively in English, iii) not allergic or intolerant to any of the sample ingredients, iv) not pregnant nor lactating, and v) willing to try plant-based meat alternatives. Data on gender, age, and diet with regards to meat consumption (i.e. meat eater, flexitarian, vegetarian, pescetarian, vegan) were also collected to characterise the study sample. Each participant took part in three sessions (~45–60 min each). Participants gave written informed consent and were offered a supermarket voucher upon completion of their visits to compensate for their time.

2.2. Sample selection

This study deliberately sought to include a wide range of PBMA products that were representative of those currently available to A-NZ consumers, that were intended to be eaten as part of a dinner type meal, and varied in their resemblance to meat.

To select the sample set, a database of all PBMA's currently available in A-NZ was created by browsing A-NZ supermarket websites and other online stores between October 2022 and January 2023. Two-hundred and forty-one products were identified, giving insight into the number of products that were available for each product type. Samples consumed and marketed as a snack (such as plant-based nuggets and jerky) and samples that would not generally be consumed on their own (such as alternatives to pate and mince) were excluded. Cold deli slices were excluded since they are unlikely to be consumed with a dinner-type meal. Furthermore, falafel, tofu, tempeh, and seitan products were excluded since these alternatives were not considered to directly replace a meat product, and often require recipes that are different from meat-containing meals. From the remaining samples, thirty-six of the most commonly available products were bench tested across four sessions, based on their availability to acquire and in proportion to the product types commercially available. Bench testing sessions were attended by 5–8 researchers from the Feast laboratory. Twenty-one products with a range of representative sensory characteristics were selected (Table 1) including eight burger patties, four sausages, four chicken alternatives, three meatball alternatives, one beef alternative, one bacon alternative and one turkey roast alternative. The turkey roast alternative contained

Table 1
Sample names, main ingredients, and images of twenty-one plant-based meat alternatives that were evaluated for affective response and sensory characteristics.

Sample name	Main ingredients	Sample block		
Beef style patty 1	TVP, pea, hemp protein	B		
Beef style patty 2	TVP, pea, hemp protein	C		
Beef style patty 3	Textured vegetable protein (TVP)	A		
Crumbed chicken style patty	Wheat, pea protein	A		
Broccoli/quinoa patty	Faba bean, pea protein	A		
Chickpea/massala patty	Chickpeas	B		




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Table 1 (continued)

Sample name	Main ingredients	Sample block		
Crumbed cauliflower patty	Cauliflower	C		
Tomato/cauliflower patty	Tomato, cauliflower	C		
Chorizo style sausage	TVP, pea, hemp protein	B		
Sage/onion sausage	Soy TVP	C		
Mushroom/grain sausage	Faba bean, pea protein	C		
Tofu based sausage	Tofu (soy beans)	A		
Meatball alternative 1	Wheat, soy, pea protein	A		
Meatball alternative 2	Soy, wheat protein	C		

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Table 1 (continued)

Sample name	Main ingredients	Sample block	
Pea/lime veggieball	Faba bean, pea protein	B	
Chicken style pieces 1	Pea protein	C	
Chicken style pieces 2	Pea protein, hemp	B	
Chicken style pieces 3	Pea protein	B	
Beef style dices	Pea, faba bean protein	B	
Bacon style rasher	Wheat, soy protein	A	
Turkey style roast	Mycoprotein, egg white, milk proteins	A	

egg white, but was included since it is a popular meat substitute brand in A-NZ and globally (Quorn™ Roast) and as such was identified as a key product for meat reduction. One product was included ahead of its release onto the market (Chicken style pieces 1).

2.3. Sensory attribute selection

Sensory attributes identified from literature (Barker and McSweeney, 2022; Carvalho et al., 2015; Coetzee, 2022; De Angelis et al., 2020; Ettinger et al., 2022; Godschalk-Broers et al., 2022; Grasso et al., 2019; Grasso et al., 2022; Mongi and Gomezulu, 2022; Neville et al., 2017; Schouteten et al., 2016; Talens et al., 2022) to describe a variety of

PBMAs were compiled into a list. This list included 49 different attributes, covering appearance (17), flavour (21), and texture/mouthfeel (17) modalities.

Bench testing sessions were conducted to evaluate attribute applicability to the study sample set, and identify any missing attributes. Up to 10 products were assessed in each session. Participants assessed each sample monadically, and selected terms relevant to each sample using a check-all-that-apply (CATA) approach. Participants were asked to note additional sensory attributes they perceived for each sample. After each sample the group discussed whether any relevant attributes to describe the sample were missing from the sensory attributes list.

New attributes frequently suggested were added to the attribute list and included, for example: 'grilled/seared appearance', 'caramelised flavour', 'gluey/slimy texture'. To ensure the final attribute list was a manageable length, two separate attributes were combined if they were regarded as synonyms by the participants, e.g., 'moist' was combined with 'juicy'.

The large variety of samples required a large number of sensory attributes. The final list included 60 attributes (Table 2) covering appearance (19 attributes), flavour (24 attributes), and texture (17 attributes) modalities. Based on the bench testing sessions and relevant literature, a definition for each attribute was developed by the researcher to ensure clarity of the terms during the consumer study (Supplementary file 1).

2.4. Emotion term selection

An emotion lexicon developed and published previously to assess emotional response to plant-based burger patties (Orr et al., 2023) was used to measure emotional response in the current study. Although the lexicon was developed specifically for plant-based burger patties, it was selected because it was comprehensive and deemed relevant to wider the PBMA category, especially since the lexicon included terms that are missing from other generic lexicons, such as 'amazed', 'deceived' and 'suspicious' (Table 2). During the bench testing session, emotional terms were checked for applicability, and participants were asked to add any

Table 2

Appearance, flavour and texture sensory attributes, and emotional terms, included in the lexicon to describe sensory characteristics of 21 plant-based meat alternatives.

Appearance	Flavour	Texture	Emotions
e	Aromatic spices	Chewy/rubbery	Adventurous
Chunky/coarse	Beany/legumes	Chunky/coarse	Afraid
e	Bitter	Crispy	Amazed
Dense/compact	Black pepper	Crumbly	Angry
Dry	Caramelised	Dense/compact	Anxious
Fibrous	Cardboard/stale	Dry	Bored
Fried	Fatty	Fibrous	Calm
Fried coating	Flavourless	Gluey/slimy	Curious
Greasy/oily	Fried	Greasy/oily	Deceived
	breadcrumbs		
Green colour	Garlic/onion	Holds together	Disappointed
Grilled/seared	Green vegetables	Moist/juicy	Disgusted
Moist/juicy	Hot spices	Pasty/doughy	Dissatisfied
Orange colour	Meat flavour	Small grains/ particles	Energetic
Pink centre	Mixed herbs	Soft	Happy
Soft	Mushroom/ earthy	Spongy	Hopeful
	Nutty	Sticky	Hungry
Visible grains	Root vegetables	Tender	Loving
Visible herbs/ vegetables			
White/cream colour	Salty		Neutral
Yellow colour	Savoury		Nostalgic
	Smoky/grilled		Pleasant
	Sour		Satisfied
	Sweet		Suspicious
	Tomato		Uncertain
	Wheaty/grainy		Unhappy

other emotional terms that they considered relevant, however, none were suggested. Participants were provided with synonyms for each emotion to ensure clarity of the emotions to the participants (Supplementary file 1).

2.5. Methodology

2.5.1. Experimental design

All participants evaluated all 21 products for: 1) overall liking and liking of appearance, flavour, and texture; 2) perceived similarity to meat; 3) emotional response; and 4) sensory characterisation of appearance, flavour, and texture. Low risk ethical requirements allowed maximum consumption of 25 % of the daily recommended intake of sodium per session, which allowed for seven samples to be tested in each session. Samples were divided into three blocks of seven products (Table 1). Rather than random allocation, each block was designed to contain a variety of product types, and included both products aiming to imitate meat products and vegetable-based products, to maintain variation in samples within a block to avoid comparison within a product type.

2.5.2. Sample preparation and presentation

Samples were either cooked between a top and bottom plate on a commercial grill (Built-in oven OB60, Fisher & Paykel, Costa Mesa, California, U.S.A) set at 180 °C, in an oven (200 °C) (High Speed Contact Grill, Roband, Sydney, NSW, Australia), or in a frying pan with canola oil, according to manufacturer instructions. A trial run prior to the study was conducted to confirm cooking times. Samples were cut into pieces, and two pieces of each sample were wrapped together in aluminium foil and coded with a random three-digit code. Serving sizes ranged between 10 and 20 g per sample, and were kept consistent between sessions for each sample. Samples were placed into a ceramic dish for serving. All samples were cooked prior to the session and held in a food warmer (E84 Food Warmer, Bakbar, New Zealand) heated to 50 ± 5 °C up to 20 min prior to the session.

Samples were presented monadically according to a balanced order following a Williams' Latin square. Each participant received two samples pieces, they were instructed to use one piece to evaluate liking and emotional response, and the second piece to evaluate sensory characteristics.

Unsalted water crackers (Carr's, Kellogg Company, United States of America) and filtered water were provided as palate cleansers. In between each sample, a minimum of a 1-minute break was enforced to allow participants time to cleanse their palate to minimise carry over effects.

2.5.3. Questionnaire

The study sessions took place in ISO standard (ISO 8589:2007) sensory booths under white light, and took place on weekdays at 11am, 1.30 pm or 4 pm. Data was collected using Compusense Cloud® Software (Compusense Inc., Ontario, Canada) via iPads. For each sample, participants first assessed the sample for appearance, flavour, texture and overall liking on a continuous 100-point scale ranging from 0 = 'dislike extremely' to 100 = 'like extremely', with a midpoint labelled 'neither like nor dislike'. Participants evaluated the sensory attributes of the sample, using CATA. Appearance, flavour, and texture attributes were presented on separate pages. Participants were instructed to "Select the words that describe the appearance (or flavour or texture) of the sample" and were required to select at least one sensory attribute for each sensory modality. Attribute order was presented according to a Williams Latin Square across participants, but the order was fixed for each participant for all samples within a session. Participants were provided with printed lists and definitions of the sensory attributes which they could refer to throughout the session (Supplementary file 1). Finally, participants rated each sample for perceived similarity to meat on a 5-point scale ranging between 'not at all meat-like' and 'extremely meat-

like’.

2.6. Data analysis

All statistical analyses were performed in R version 4.3.0 using R Studio software version 2022.12.0.353 (R Core Team, 2022). Packages dplyr (Wickham et al., 2022) and factoextra (Kassambara and Mundt, 2020) were used for data handling and visualisation. An α risk of 0.05 was considered statistically significant and mean \pm standard deviation (SD) values are presented.

2.6.1. Similarity to meat

Meat likeness scores (columns) were cross-tabulated by sample (row) and a Chi square test was applied to understand the effect of sample on perceived meat likeness. Samples were divided into three categories: i) those perceived by at least 50 % of the participants to be ‘extremely’ or ‘very’ meat-like, ii) those perceived by at least 50 % of the participants to be ‘not at all’ or ‘not very’ meat-like, and iii) those rated in between.

2.6.2. Understanding variation in liking and contribution of each sensory modality across the sample space

To determine sample differences in overall liking ratings, a mixed effects model, with overall liking ratings as a response variable; sample number as the fixed factor; and participant as the random factor, was performed using the nlme package (Pinheiro et al., 2022). To determine the contribution of appearance, flavour and texture liking modalities on the overall liking of a sample, a linear model with overall liking ratings as the response variable; and sample number, appearance, flavour, and texture liking ratings, as fixed factors, allowing for interactions between sample and each liking modality, was performed. R squared (R^2) and Akaike Information Criterion (AIC) values of models including each of the liking types alone, and in combination with each other, were compared to determine the model that best predicted overall liking ratings. Correlations between all liking modalities and perceived similarity to meat were determined with Spearman’s correlation.

2.6.3. Sample differences in sensory and emotional characteristics and their associated relationships

For each sample, citation scores for emotional and sensory attributes were calculated by dividing the total selection frequency by the number of participants. To determine whether the selected frequency of a sensory or emotional attribute differed between samples, a generalised linear model (binomial family) was performed, with the sensory or emotional attribute as the response variable and the sample as the fixed factor. Post hoc comparisons with Tukey adjustments for multiple comparisons were conducted when a significant effect of sample was found. Since sample main effects were present for most attributes, a principal component analysis (PCA; stats package) including all of the sensory attributes (i.e. appearance, flavour and texture attributes) was conducted to determine what was driving variation in the product space. The prcomp function uses singular value decomposition, and no rotation was applied. A correlation matrix was obtained to determine the correlation between each sensory attribute and each PC. To visualise drivers of liking, appearance, flavour, texture, overall liking ratings, and perceived similarity to meat were projected as supplementary variables on the biplot of the PCA on sensory attributes (Kassambara and Mundt, 2020). Additional PCAs were performed on appearance, flavour and texture attributes separately to further understand variation across each modality. A final PCA was also applied to the emotional response attributes. To illustrate the relationship between sensory characteristics and emotional response, sensory attributes were projected as supplementary variables on the emotional response PCA. All PCAs were conducted using citation proportions for sensory and emotional attributes.

2.6.4. Determining sensory drivers of liking and perceived similarity to meat

Sensory attributes driving liking and perceived similarity to meat

were determined by running a linear model, with overall liking as the response variable and the 60 sensory attributes as the fixed factors. The contribution of each attribute towards overall liking was determined by the regression coefficient of each attribute, and the p-value determined whether the contribution to liking was significant.

3. Results

3.1. Participants

The study was completed by 140 consumers (37 men, 103 women) with a median age of 35 ± 9 years and, for information, who self-reported a range of dietary behaviours (58 omnivores, 65 flexitarians, and 17 meat-avoiders (1 pescetarian, 8 vegetarians, 8 vegans). The number of completions per sample block was not completely balanced due to unavoidable rescheduling of visits by the participants. Each sample block was completed between 19 and 27 times (ABC: 27; ACB: 26; BAC: 22; BCA: 21; CAB: 19; CBA: 25).

3.2. Perceived similarity to meat of the samples

Median scores for perceived similarity to meat ranged between 1 and 4 (Table 3), with the majority of the samples having a median score of 3 (10 samples). Five samples had a median score of 3.5 or 4, representing scores that are above the ‘somewhat meat-like’ label on the 5-point scale, whereas four samples had a median score of 1 – representing ‘not at all meat-like’. Chi-square testing determined that meat likeness was different between samples ($\chi^2 = 1903.3$, $p < 0.001$). Seven were rated by at least 50 % of the participants to be ‘very’ or ‘extremely’ meat-like. In contrast, eight samples were perceived by at least 50 % of the participants to be ‘not very’ or ‘not at all’ meat-like (Fig. 1).

3.3. Appearance, flavour, texture and overall liking ratings

Appearance, flavour, texture, and overall liking ratings were not affected by sample block order ($p > 0.05$), but were affected by the sample position within each block ($p < 0.001$), highlighting the importance of using a balanced sample presentation order. Mean overall liking ratings ranged from 77.7 ± 17.4 for Beef style patty 1, made from TVP, pea, and hemp protein, to 35.1 ± 1.2 for the Mushroom/grain sausage, made from wholefood ingredients (Table 3, Fig. 2). Fifteen products were, on average, rated at or above the neutral mark (50/100), but only two products were rated above the 75-point mark (Beef style patty 1 and Crumbed chicken style patty). Differences in overall liking were detected between samples in the same product category (Fig. 2). For example, beef-style patty 1 was better liked than beef-style patty 2, meatball alternative 1 was better liked than meatball alternative 2, and the chorizo-style sausage was better liked than the sage/onion sausage. In contrast, all chicken style pieces were similarly liked.

Although the products perceived to be ‘not at all’ or ‘not very’ meat-like were generally liked least, 24 % (Mushroom/grain sausage) to 55 % (Tomato/cauliflower patty) of participants rated such products above the neutral mark (50/100) on the scale (Table 3). However, the proportion of participants that rated these samples above the three-quarter mark (75/100) was only 14 % at the most (for the Chickpea/masala patty and Tofu based sausage).

The R^2 value of the model to predict overall liking ratings, in comparison to a baseline model only containing sample number as a dependent variable ($R^2 = 0.25$; Table 4), increased most when flavour liking was added ($R^2 = 0.84$), followed by texture liking ($R^2 = 0.76$), and lastly appearance liking ($R^2 = 0.45$). When a combination of liking modalities was added, R^2 was highest for the combination of flavour liking and texture liking ($R^2 = 0.93$), compared to the combinations of appearance and flavour ($R^2 = 0.85$) or appearance and texture ($R^2 = 0.77$) likings, and R^2 did not further improve when appearance liking was added to the flavour/texture model ($R^2 = 0.93$). In accordance with

Table 3

Perceived similarity to meat, appearance, flavour, texture and overall liking (mean +/- standard deviation), and percentage of participants rating samples at the neutral or 75-point mark of the 100-point overall liking scale.

	Perceived similarity to meat (median, (interquartile range))	Liking ratings				p-value ¹	Percentage participants rating overall liking:	
		Appearance liking	Flavour liking	Texture liking	Overall liking		≥50 ²	≥75 ³
Beef style patty 1	4.0(1)	70.1 ± 19.6	76.8 ± 17.6	75.2 ± 17.9	77.7 ± 17.4	<0.001	94 %	61 %
Beef style patty 2	3.0(1)	74.5 ± 14.8	68.9 ± 19.8	64.2 ± 20.7	68.3 ± 20.0	<0.001	84 %	41 %
Beef style patty 3	4.0(2)	71.8 ± 19.2	75.6 ± 17.8	70.5 ± 20.9	74.3 ± 18.7	<0.001	89 %	54 %
Crumbed chicken style patty	4.0(1)	78.6 ± 16.1	75.9 ± 16.1	73.7 ± 17.2	76.9 ± 16.4	<0.001	94 %	57 %
Broccoli/quinoa patty	1.0(1)	36.5 ± 23.1	40.7 ± 21.5	35.3 ± 19.7	37.0 ± 21.1	0.002	32 %	4 %
Chickpea/masala patty	1.0(0)	52.5 ± 21.2	53.0 ± 24.4	43.7 ± 21.8	49.3 ± 22.8	<0.001	52 %	14 %
Crumbed cauliflower patty	2.0(1)	59.5 ± 23.4	48.0 ± 23.5	44.9 ± 20.5	45.1 ± 23.1	<0.001	42 %	13 %
Tomato/cauliflower patty	2.0(1)	54.2 ± 22.1	54.3 ± 22.1	44.4 ± 21.2	50.0 ± 21.8	<0.001	55 %	11 %
Chorizo style sausage	3.0(1)	67.9 ± 18.9	67.9 ± 19.7	66.8 ± 20.5	67.5 ± 19.5	0.850	81 %	39 %
Sage/onion sausage	3.0(1)	69.0 ± 19.9	56.6 ± 22.6	59.8 ± 22.0	56.8 ± 22.7	<0.001	64 %	21 %
Mushroom/grain sausage	1.0(1)	38.8 ± 22.4	38.2 ± 21.8	34.8 ± 20.8	35.1 ± 21.2	0.018	24 %	3 %
Tofu based sausage	3.0(1)	69.0 ± 15.6	51.2 ± 20.2	53.4 ± 21.1	50.8 ± 20.2	<0.001	50 %	14 %
Meatball alternative 1	3.0(1)	67.4 ± 17.2	63.6 ± 20.3	65.1 ± 17.4	64.8 ± 18.8	0.040	76 %	34 %
Meatball alternative 2	3.0(1)	69.1 ± 17.0	52.9 ± 21.0	60.8 ± 18.9	55.3 ± 19.7	<0.001	63 %	16 %
Pea/lime veggieball	1.0(1)	47.0 ± 22.9	42.7 ± 23.1	38.2 ± 23.1	38.7 ± 21.8	<0.001	31 %	6 %
Chicken style pieces 1	3.0(1)	59.0 ± 22.8	59.0 ± 22.8	50.0 ± 25.2	56.0 ± 23.3	<0.001	60 %	21 %
Chicken style pieces 2	3.0(2)	54.4 ± 22.7	54.4 ± 21.9	52.4 ± 24.7	53.7 ± 22.7	0.560	64 %	17 %
Chicken style pieces 3	3.0(1)	56.5 ± 23.2	45.4 ± 22.6	50.2 ± 23.1	48.4 ± 21.6	<0.001	51 %	14 %
Beef style dices	3.0(1)	59.4 ± 25.7	54.8 ± 21.0	59.8 ± 20.7	56.5 ± 20.0	0.018	66 %	18 %
Bacon style rasher	4.0(1)	59.6 ± 23.2	71.4 ± 19.1	62.6 ± 21.5	67.6 ± 20.1	<0.001	83 %	35 %
Turkey style roast	3.5(1)	49.0 ± 22.4	65.8 ± 20.8	58.9 ± 24.2	62.9 ± 22.2	<0.001	77 %	32 %

¹ p-values for the overall effects of liking modality were determined with generalised linear models (Gaussian family), with the liking scores (0–100) as the response variable, and the liking modality (i.e. appearance, flavour, texture, overall liking) as the fixed factors.

^{2,3} The percentage of participants rating a sample at the 50-point neutral mark (²), or 75-point mark (³) of the 100-point scale for overall liking ratings.

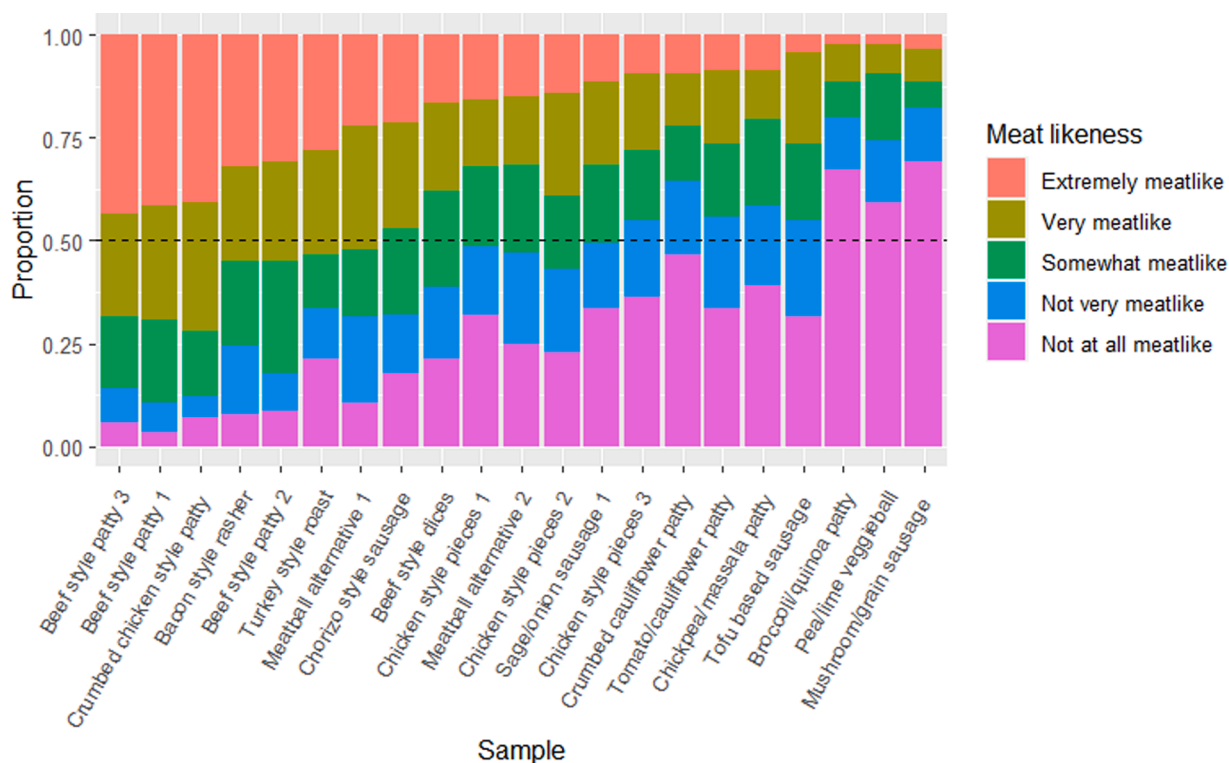


Fig. 1. Perceived meat likeness of 21 plant-based meat alternatives, ordered from most to least meat-like. The horizontal dashed line indicates the 50% mark.

these findings, flavour and texture liking ratings correlated strongly with overall liking ratings ($r \geq 0.85$), but less strongly with liking ratings for appearance ($r = 0.56$; Table 5).

3.4. Emotional response

The GLMs performed on each individual emotional attribute determined that citation proportions differed between samples for all of the 24 emotion terms (main effect of sample; all $p < 0.001$). Comparisons of emotion attribute citation proportions between samples are provided in

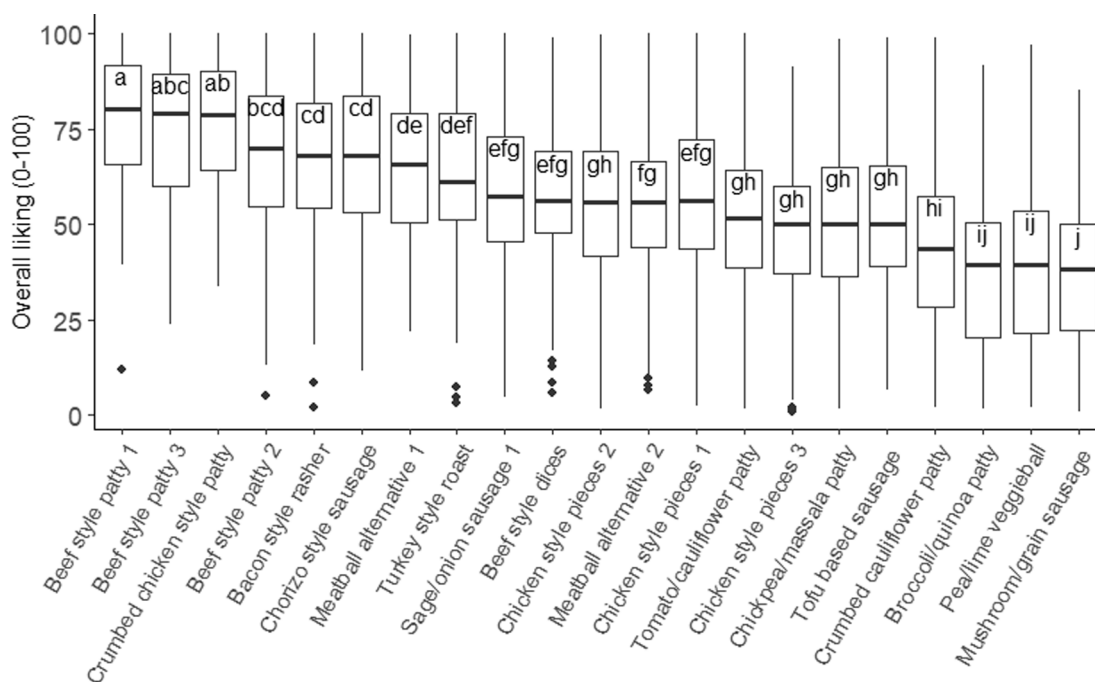


Fig. 2. Boxplot of overall liking ratings of twenty-one plant-based meat alternatives, ordered from most to least liked samples. The midline of the box indicates the median, with the lower and upper boundary of the boxes representing the 25th and 75th percentile respectively. Whiskers represent the 10 and 90th percentiles. Closed diamonds represent outliers. ^{a-j} sample with different letter codes are significantly different adjusted with Tukey corrections for multiple comparisons ($p < 0.05$).

Table 4

R squared and Akaike Information Criterion for models predicting overall liking ratings, with appearance, flavour, and texture liking ratings, alone and in combination, as fixed factors.

Factor	R squared (R ²)	AIC
Sample	0.25	26,213
Sample + appearance liking	0.45	25,351
Sample + flavour liking	0.84	21,753
Sample + texture liking	0.76	22,857
Sample + appearance liking + flavour liking	0.85	21,456
Sample + appearance liking + texture liking	0.77	22,738
Sample + flavour liking + texture liking	0.93	19,381
Sample + appearance liking + flavour liking + texture liking	0.93	19,350

To determine R-squared values, linear models were performed, with overall liking ratings (0–100) as the response variable, and appearance, flavour, and texture liking ratings (0–100) as the fixed factors (alone or in combination).

Supplementary file 2.

PCA of the citation proportions of emotions was nearly one-dimensional, with PC1 explaining 82 % of the variation, and PC2 explaining 6.5 % of the variation. PC1 separated samples according to emotion valence (Fig. 3A, Table 6). In general, samples that were perceived to be ‘extremely’ or ‘very’ meat-like were associated with

Table 5

Spearman’s Correlation coefficients between liking modalities and perceived similarity to meat, and to principal component1 of the principal component analysis including all sensory attributes.

	Appearance liking	Flavour liking	Texture liking	Overall liking	Perceived similarity to meat	Correlation to PC1 ¹
Appearance liking	NA					−0.60
Flavour liking	0.48	NA				−0.74
Texture liking	0.55	0.69	NA			−0.77
Overall liking	0.56	0.91	0.85	NA		−0.78
Perceived similarity to meat	0.47	0.58	0.64	0.66	NA	−0.89

¹ PC1 of the PCA including all sensory attributes.

positive emotion terms, such as ‘satisfied’, ‘happy’, ‘hopeful’, ‘pleasant’, and ‘amazed’, whereas the samples that were perceived as ‘not at all’ or ‘not very’ meat-like were associated with negative emotion terms on the positive pole, such as ‘dissatisfied’, ‘disappointed’, ‘uncertain’, and ‘unhappy’. PC2 related to arousal, ranging from ‘adventurous’ and ‘anxious’ to ‘calm’ and ‘neutral’. Samples that were perceived as ‘somewhat’ meat-like were spread across PC2, with chicken-style pieces associated with low arousal terms such as ‘hopeful’, ‘calm’, ‘neutral’ and ‘bored’; beef style dices associated with activated negative emotions such as ‘suspicious’ and ‘disgusted’; and the chorizo style sausage with activated positive terms such as ‘energetic’, ‘curious’, and ‘adventurous’.

3.5. Sensory sample characterisation

The GLMs performed on each individual sensory attribute determined that citation proportions differed between samples for all of the 60 sensory attributes (main effect of sample; all $p < 0.001$). Sensory attribute citation proportions per sample are presented in [Supplementary file 2](#).

3.5.1. PCA across all sensory attributes

The negative pole of PC1 (35.2 %) was associated with ‘fatty flavour’, ‘meat flavour’, ‘greasy/oily texture’, and ‘savory flavour’ (Fig. 4A, Table 6). In contrast, the positive pole was associated with terms such as ‘visible herbs/vegetables’, ‘visible grains’, ‘small grains/

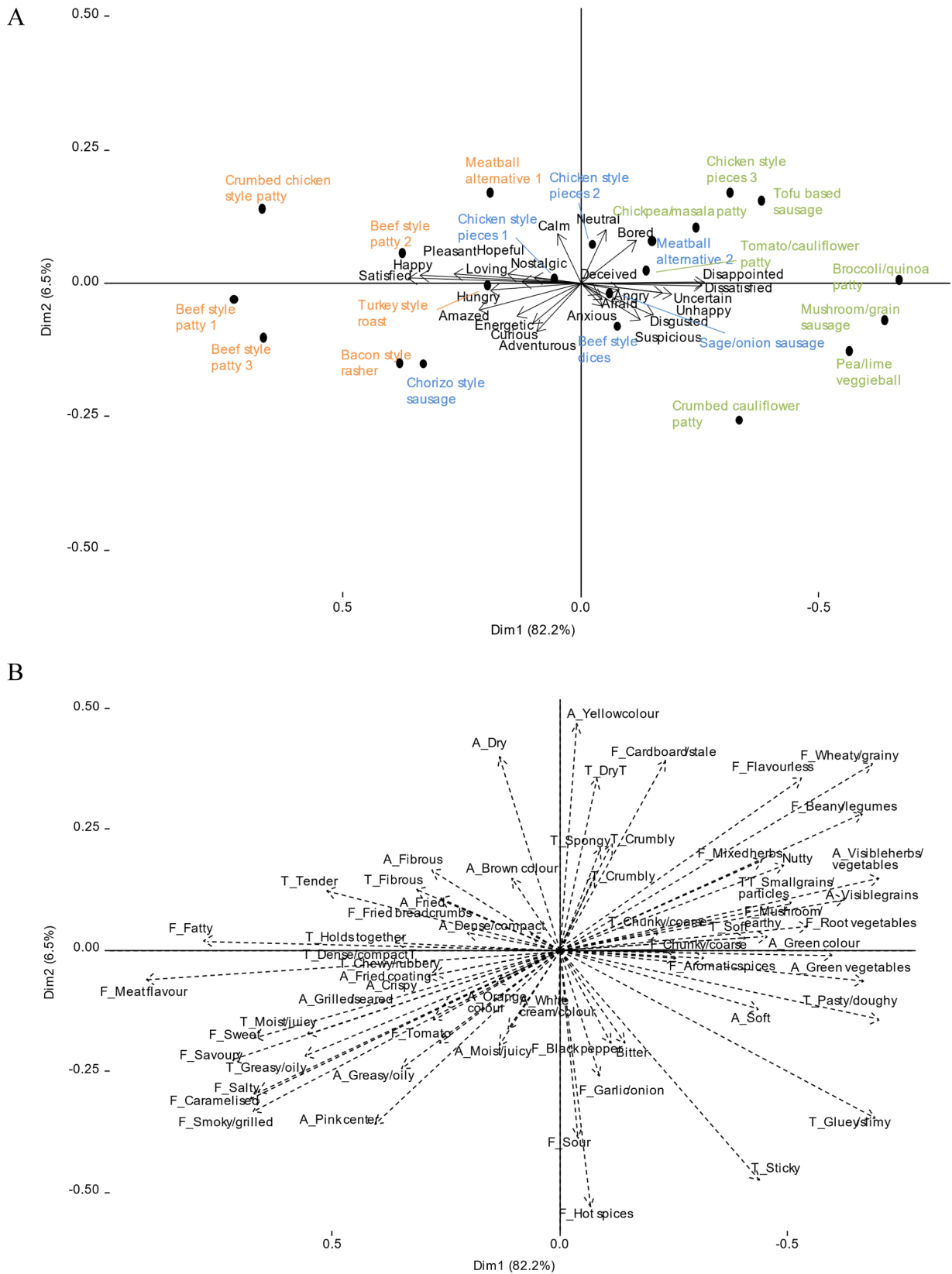


Fig. 3. A: Principal component analysis (PCA) biplot of principal components (PC) 1 and 2 presenting emotion attribute association with twenty-one plant-based meat alternative samples. Green samples (n = 8) are those perceived to be not at all or not very meat-like; orange samples (n = 7) are those perceived to be extremely or very meat-like, and blue samples (n = 6) are those perceived to be somewhat meat-like. B) Positioning of sensory attributes as supplementary variables on the biplot of principal components 1 and 2 presenting emotion attribute association.

Table 6

Correlation of attributes to principal components 1 to 4 of i) principal component analysis including all sensory attributes combined, and ii) separate principal component analyses for each sensory modality.

	PC1				PC2				PC3				PC4			
	Negative pole		Positive pole		Negative pole		Positive pole		Negative pole		Positive pole		Negative pole		Positive pole	
	Attribute	r	Attribute	r	Attribute	r	Attribute	r	Attribute	r	Attribute	r	Attribute	r	Attribute	r
Emotions	Satisfied	-0.98	Dissatisfied	0.96												
	Happy	-0.97	Disappointed	0.95												
	Hopeful	-0.97	Uncertain	0.95												
	Pleasant	-0.97	Unhappy	0.94												
	Amazed	-0.95	Deceived	0.86												
	Hungry	0.95	Disgusted	0.81												
	Loving	0.94	Suspicious	0.77												
	Nostalgic	0.85	Bored	0.76												
	Energetic	0.83	Angry	0.74												
	Adventurous	0.63	Afraid	0.63												
	Curious	0.57	Anxious	0.63												
All sensory attributes combined	Fatty flavour	-0.90	Visible herbs/vegetables	0.92	Brown colour	-0.83	Fried coating	0.83	Tomato flavour	-0.77	Cardboard/stale flavour	0.75	Soft appearance	-0.68	Dry texture	0.83
	Meat flavour	-0.85	Visible grains	0.91	Grilled/seared appearance	-0.77	Fried breadcrumb flavour	0.82	Orange colour	-0.67	Spongy texture	0.68	Soft texture	0.58	Dry appearance	0.73
	Greasy/oily texture	-0.71	Small grains/particles	0.88	Dense/compact appearance	-0.74	Crispy appearance	0.77	Hot spices	-0.59	Flavourless	0.62			Crumbly texture	0.56
	Savoury flavour	-0.66	Wheaty/grainy flavour	0.83	Dense/compact texture	-0.62	Fried appearance	0.76	Sour flavour	-0.57	Fibrous appearance	0.56				
	Salty flavour	-0.64	Green vegetable flavour	0.80	Holds together	-0.59	Crumbly appearance	0.58	Sweet flavour	0.57						
	Chewy/rubbery texture	-0.62	Pasty/doughy texture	0.75			Crumbly texture	0.55	Smoky/grilled flavour	-0.55						
	Fibrous texture	-0.61	Root vegetable flavour	0.75												
	Caramelised flavour	-0.61	Green colour	0.75												
	Smoky/grilled flavour	-0.59	Mixed herb flavour	0.75												
	Fibrous appearance	-0.58	Beany/legume flavour	0.73												
			Gluey/slimy texture	0.66												
Appearance attributes	Fried	-0.78	Visible herbs/vegetables	0.77	Visible grains	-0.63	Pink centre	0.66	White/cream colour	-0.64	Orange colour	0.69	Dry	-0.86	Moist/juicy	0.62
	Fried coating	-0.71	Dense/compact	0.69	Visible herbs/vegetables	-0.58	Greasy/oily	0.65	Soft	-0.58	Crumbly	0.62				
			Visible grains	0.69			Grilled/seared	0.62								
			Brown colour	0.68			Fibrous	0.58								
			Chunky/coarse	0.59			Moist/juicy	0.57								
Flavour attributes	Wheaty/grainy	-0.85	Meat flavour	0.91	Black pepper	-0.81	Brown colour	0.56	Mushroom/earthy	-0.58	Fried breadcrumbs	0.83	Tomato	-0.62		
							Cardboard/stale	0.77								

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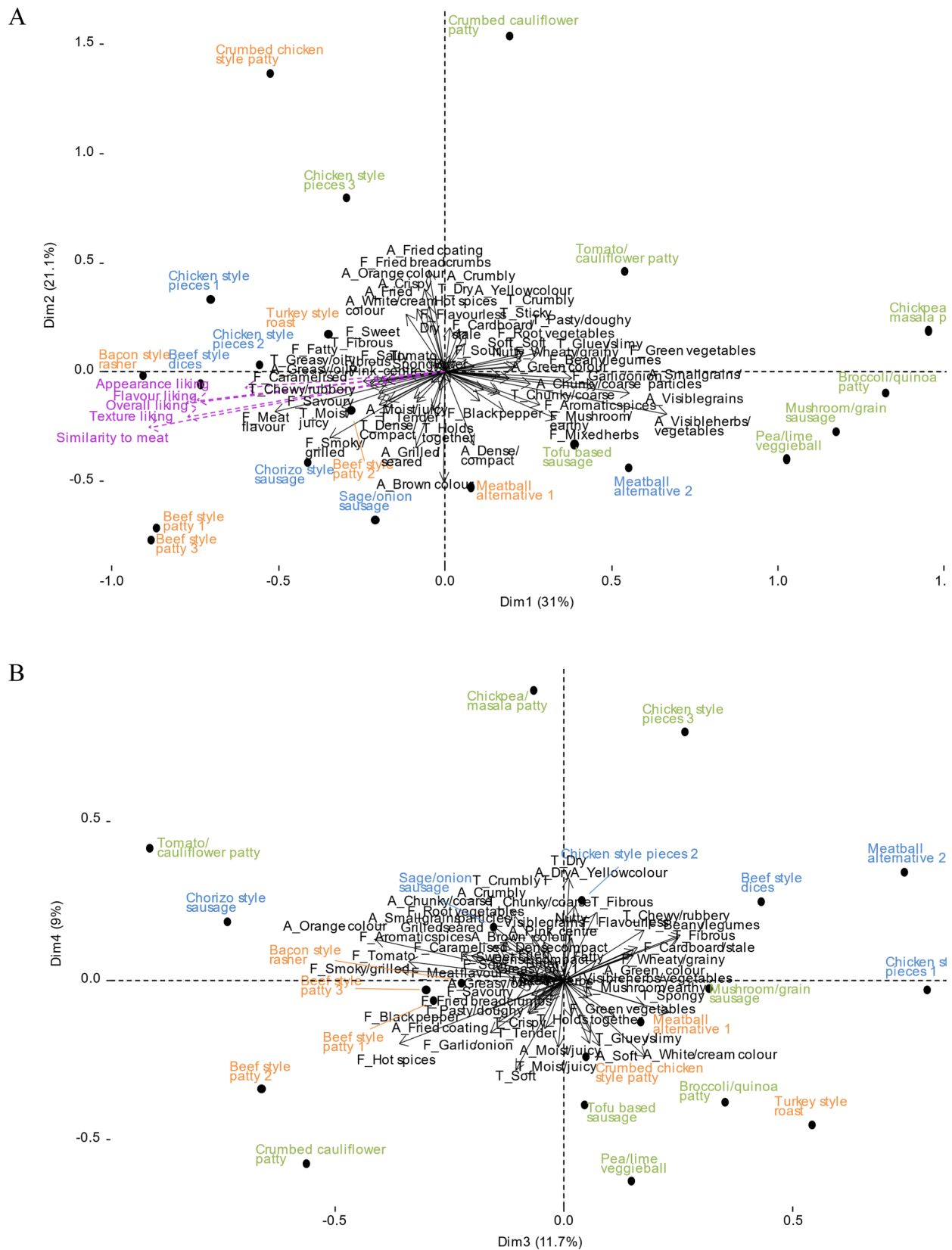


Fig. 4. Principal component analysis biplot of principal components 1 and 2 (A), and principal components 3 and 4 (B) presenting sensory attributes associated with twenty-one plant-based meat alternative samples. A, appearance; F, flavour; T, texture. Green samples (n = 8) perceived to be not at all or not very meat-like; orange samples (n = 7) perceived to be extremely or very meat-like, and blue samples (n = 6) perceived to be somewhat meat-like by at least 50 % of the participants. Appearance, flavour, texture, and overall liking ratings, and perceived similarity to meat, added as supplementary variables in pink.

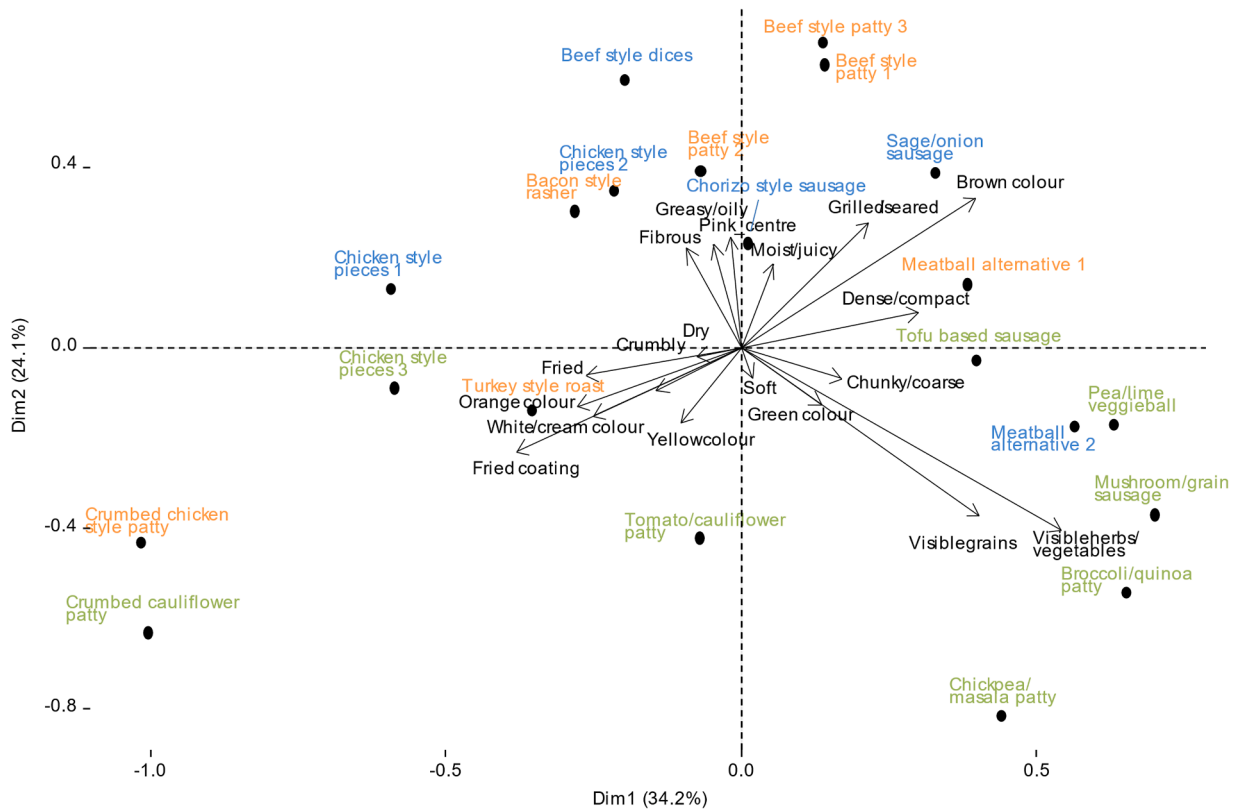


Fig. 5. Principal component analysis biplot of principal components 1 and 2 presenting appearance attributes associated with twenty-one plant-based meat alternative samples. Green samples (n = 8) perceived to be not at all or not very meat-like; orange samples (n = 7) perceived to be extremely or very meat-like, and blue samples (n = 6) perceived to be somewhat meat-like by at least 50 % of the participants.

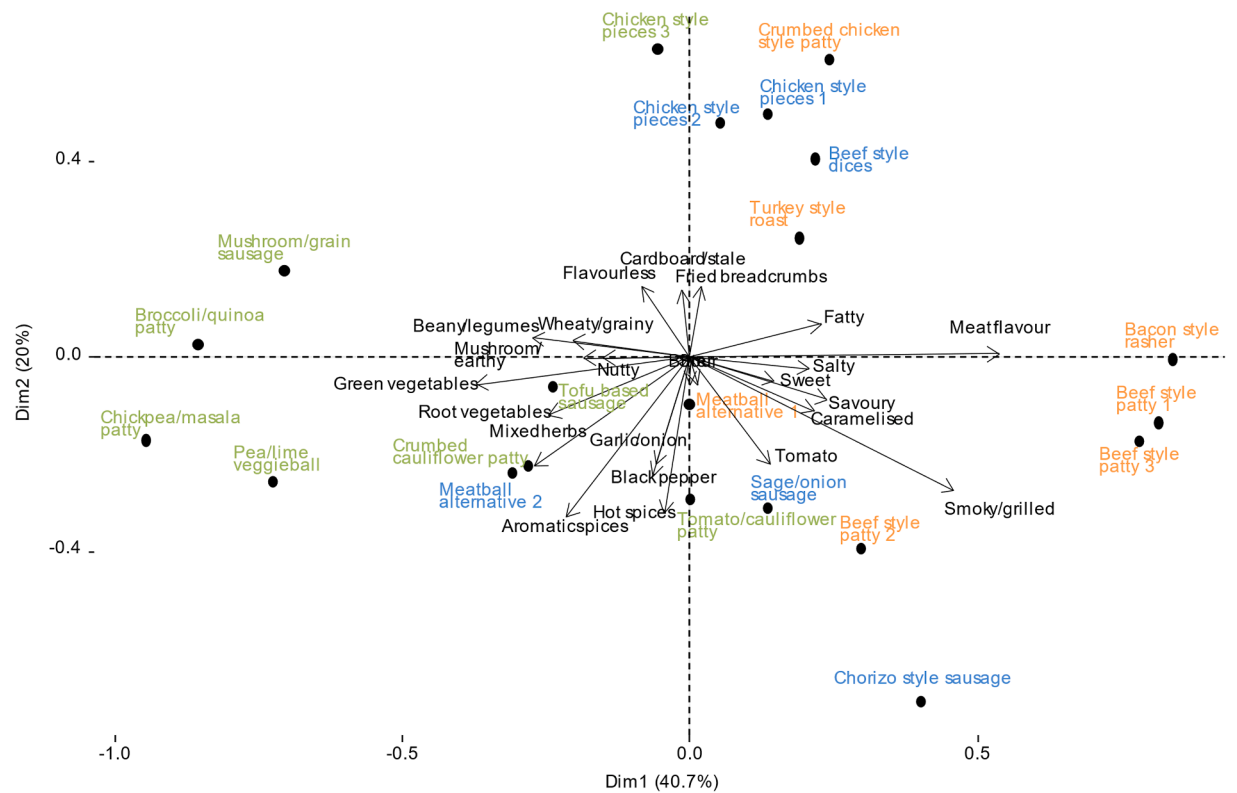


Fig. 6. Principal component analysis biplot of principal components 1 and 2 presenting flavour attributes associated with twenty-one plant-based meat alternative samples. Green samples (n = 8) are those perceived to be not at all or not very meat-like; orange samples (n = 7) perceived to be extremely or very meat-like, and blue samples (n = 6) perceived to be somewhat meat-like by at least 50 % of the participants.

absence of fried flavours (PC3), and tomato flavours (PC4). PC2 to PC4 did not separate samples based on perceived likeness to meat, and as such terms are not necessarily indicative of a sample's (dis)similarity to meat.

3.5.4. Texture

The first four dimensions of the PCA on texture attributes explained 81.6 % of the variation in sample texture. PC1 (38.8 %; Fig. 7, Table 6) captured variation in chewiness of the samples, and spanned from 'chewy/rubbery' and 'fibrous' to 'pasty/doughy', 'small grains/particles', 'soft', 'sticky', and 'gluey/slimy'. PC2 (19.4 %; Fig. 7) captured moistness of the samples, ranging from 'moist/juicy' and 'tender' to 'dry', and 'crumbly'. PC3 (14.9 %; Supplementary file 3) separated 'chunky/coarse' and 'dense/compact' from 'crispy' textures. PC4 (8.5 %; Supplementary file 3) correlated with 'dense/compact' ($r = 0.53$) on the positive pole and to 'spongy' ($r = -0.54$) on the negative pole albeit at lower correlation coefficients. PC1 separated samples based on their perceived similarity to meat, whereas PC2 and PC3 separated samples based on moistness (PC2) and compactness (PC3). Texture attributes associated with PC2 to PC4 did not separate samples based on perceived likeness to meat, and as such terms relating to these PCs are not indicative of a sample's (dis)similarity to meat.

3.5.5. Associations between sensory attributes and emotional response

The overlay of the sensory attributes (Fig. 3B) as supplementary variables indicated that sensory attributes associated with meat likeness were key drivers of the division between positive and negative emotions along PC1. Positive emotions were associated with sensory attributes such as 'meat flavour', 'fatty', moist/juicy', and 'tender', whereas negative emotions were associated with 'green colour', 'green vegetables', 'pasty/doughy', and 'visible grains and herbs/vegetables'. Differences in perception relating to blandness and spiciness likely contributed to the separation of samples across PC2. For example, the chorizo style sausage, bacon style rasher, beef style dices, and crumbed

cauliflower patty were associated with activated positive and negative terms such as 'energetic', 'curious', and 'adventurous', and 'disgusted' and 'suspicious', respectively. The chorizo-style sausage and crumbed cauliflower burger were the two samples that scored highest for 'hot spices', and bacon was the sample that scored highest for 'salty' and 'smoky/grilled' flavour (Supplementary file 2). In contrast, all chicken style piece samples scored high for 'cardboard/stale' and Chicken style pieces 3 was the sample that scored highest for 'flavourless'. Lack of intense flavour may have caused the chicken piece samples to place on the opposite end of PC2 associated with deactivated terms including 'bored' and 'neutral'.

3.6. Sensory drivers of liking

Of all sensory drivers significantly contributing to overall liking ($n = 26$), most ($n = 12$) were flavour attributes (Table 7) – the largest driver being 'meat flavour' (regression coefficient (RC): 13.1).

Other flavour attributes that contributed positively to overall liking were: 'fried breadcrumbs', 'caramelised', 'smoky/grilled', 'fatty', 'sweet', 'tomato', and 'savory'. Flavour attributes that negatively contributed to overall liking were: 'cardboard/stale', 'flavourless', 'bitter', and 'sour'. The absence of 'gluey/slimy', followed by 'pasty/doughy', and 'sticky' were the main texture drivers of liking, however the presence of 'crispy', 'moist/juicy', 'tender', and 'holds together' also contributed. Appearance attributes contributed less to overall liking than flavour and texture attributes, where 'visible grains' and 'fried' contributed negatively and positively, respectively.

There was a large similarity between drivers for liking and drivers for perceived similarity to meat (Supplementary file 4), likely explained by a strong ($r = 0.92$, $p < 0.001$) correlation between sample liking and 'meat flavour' (Fig. 8). The correlation plot shows clear sample groupings according to their perceived similarity to meat: samples with low overall liking scores were those perceived not similar to meat (Fig. 8: samples in green font), and also had low citation proportions for meat

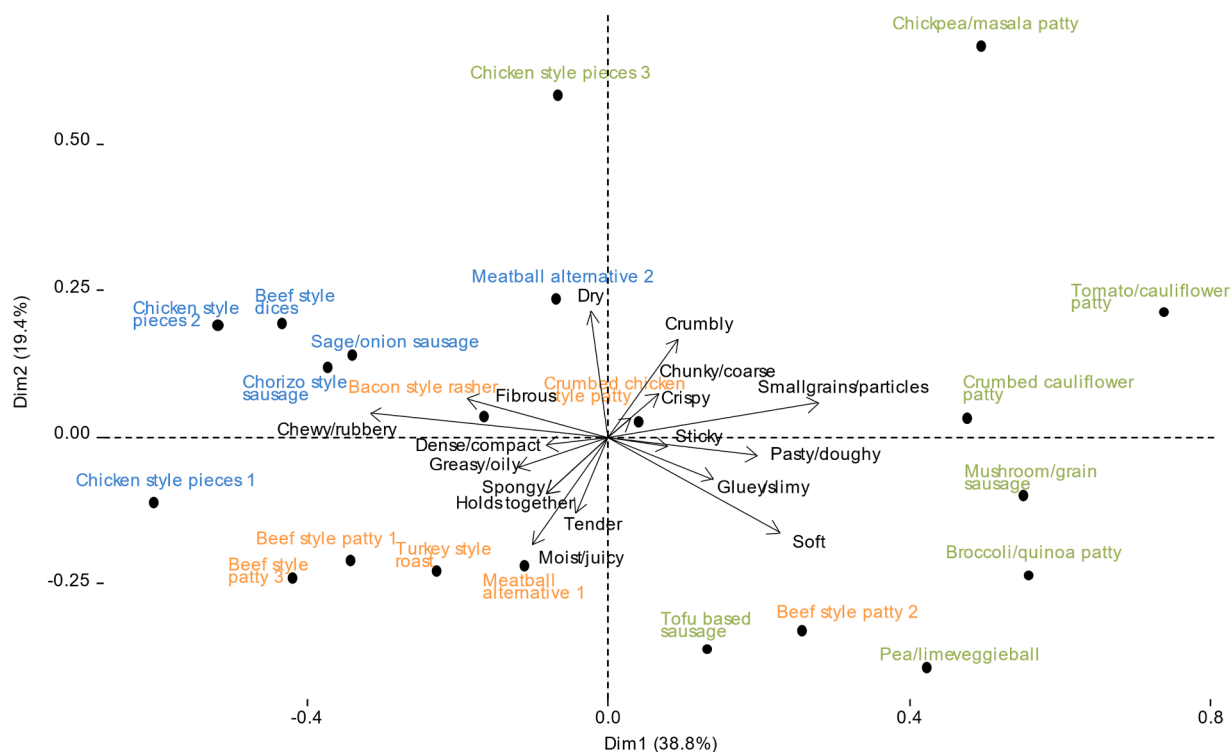


Fig. 7. Principal component analysis biplot of principal components 1 and 2 presenting texture attributes associated with twenty-one plant-based meat alternative samples. Green samples ($n = 8$) are samples that were perceived to be not at all or not very meat-like; orange samples ($n = 7$) are samples that were perceived to be extremely, or very meat-like, and blue samples ($n = 6$) are samples that were perceived to be somewhat meat-like by at least 50 % of the participants.

Table 7

The contribution to overall liking of 60 sensory drivers relating to appearance, flavour, and texture, as determined by the regression coefficient from a generalised linear model predicting overall liking.

Appearance attribute	Contribution to liking ¹	p-value ²	Flavour attribute	Contribution to liking	p-value	Texture attribute	Contribution to liking	p-value
Visible grains	-2.4	0.021	Meat flavour	13.1	<0.001	Gluey/ slimy	-9.9	<0.001
Fried	2.4	0.01	Cardboard/ stale	-8.9	<0.001	Pasty/ doughy	-6.2	<0.001
Dry	-2.2	0.023	Flavourless	-6.5	<0.001	Crispy	5.0	0.002
Visible herbs/ vegetables	-2.13	0.04	Fried breadcrumbs	6.1	<0.001	Moist/ juicy	4.8	<0.001
Dense/ compact	2.03	0.014	Bitter	-5.3	<0.001	Tender	4.1	<0.001
Yellow colour	1.86	0.14	Caramelised	4.4	<0.001	Sticky	-3.5	0.006
Brown colour	1.59	0.05	Smoky/ grilled	3.8	<0.001	Holds together	3.1	<0.001
Greasy/ oily	-1.51	0.1	Sour	-3.8	0.023	Chewy/ rubbery	-2.2	0.008
Pink centre	1.35	0.29	Sweet	3.0	0.005	Spongy	1.34	0.13
Fibrous	0.85	0.41	Fatty	2.2	0.023	Dry	-1	0.35
Grilled/ seared	-0.69	0.38	Tomato	2.35	0.037	Soft	-0.8	0.33
White/ cream colour	-0.66	0.57	Wheaty/ grainy	1.86	0.057	Greasy/ oily	-0.8	0.44
Moist/ juicy	0.56	0.54	Savoury	1.61	0.047	Small grains/ particles	0.7	0.46
Chunky/ coarse	-0.53	0.6	Beany/ legumes	-1.6	0.067	Crumbly	0.6	0.60
Orange colour	0.49	0.61	Hot spices	-1.41	0.18	Chunky/ coarse	-0.5	0.63
Soft	-0.38	0.66	Mushroom/ earthy	-1.06	0.23	Dense/ compact	-0.4	0.60
Crumbly	-0.39	0.75	Nutty	-0.86	0.41	Fibrous	0.2	0.85
Green colour	-0.33	0.85	Green vegetables	-0.85	0.49			
Fried coating	0.14	0.92	Root vegetables	-0.74	0.48			
			Salty	0.69	0.4			
			Black pepper	-0.64	0.52			
			Mixed herbs	0.59	0.5			
			Garlic/ onion	0.5	0.55			
			Aromatic spices	-0.13	0.89			

¹ Contribution determined by the regression coefficients of each attribute within a generalised linear model, in which overall liking rating (0–100) was the response variable, and the binary check-all-that-apply scores of the sensory attributes were the fixed factors.

² P-values represent the associated significance for inclusion in the model. Significant drivers are stated in bold.

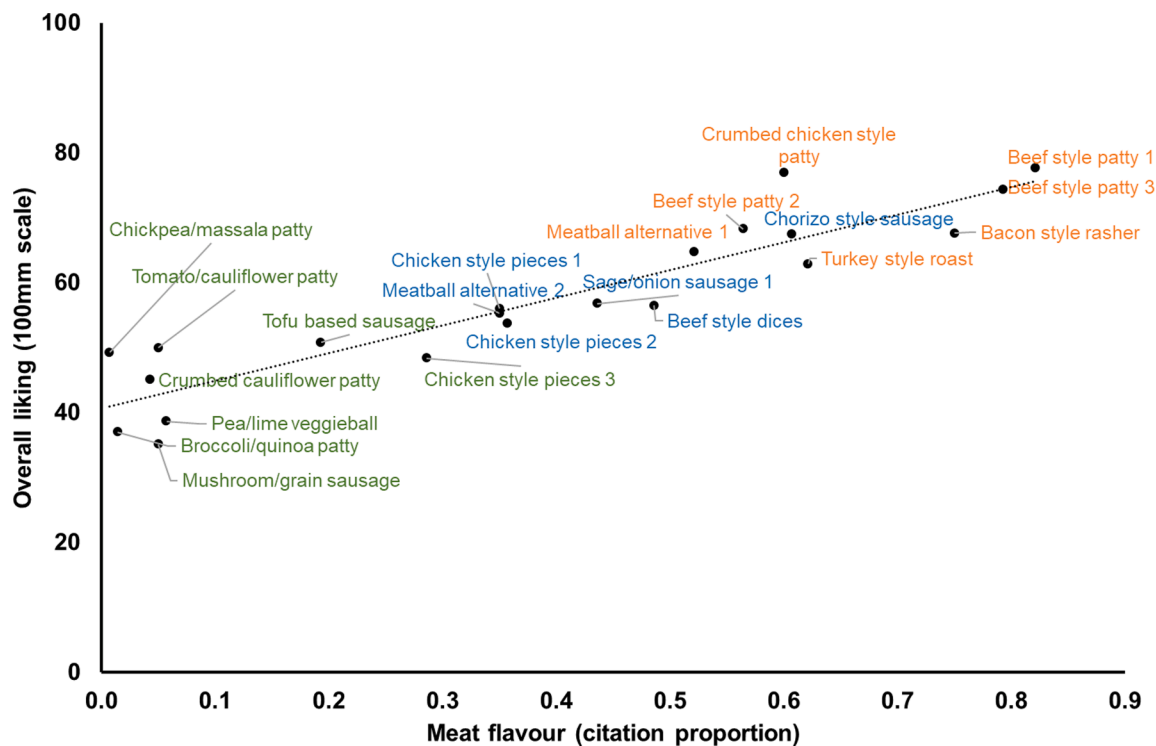


Fig. 8. Scatter plot of perceived meat flavour (citation proportions) and overall liking ratings ($r = 0.92$, $p < 0.001$). Green samples ($n = 8$) are those perceived to be not at all or not very meat-like; orange samples ($n = 6$) are those perceived to be extremely or very meat-like, and blue samples ($n = 7$) are those perceived to be somewhat meat-like.

flavour. Conversely, samples with high overall liking scores were characterised by a high perceived similarity to meat (Fig. 8: samples in orange font), and rated highly for meat flavour.

4. Discussion

To date this is the first study to have profiled a wide range of PBMA representative of a market (A-NZ market), with regards to similarity to meat, product acceptance, emotional response, and sensory characteristics. This study established that commercially available PBMA, in A-NZ, vary widely in their perceived similarity to meat, and appearance, flavour, and texture characteristics. Samples spanned a wide range for all liking modality ratings, perceived similarity to meat, and sensory attributes, confirming that a broad range of products was evaluated in the study. Sample liking was strongly affected by perceived similarity to meat, with overall liking mostly driven by flavour and texture liking, and to a lesser extent appearance liking. In terms of sensory attributes, meat flavour was the strongest driver of liking. Although low consumer acceptance of PBMA sensory characteristics are often cited as a barrier for uptake (Onwezen et al., 2021), this study showed that there are products acceptable to A-NZ consumers, particularly if they resembled a meat product. Samples with the highest liking ratings included beef style and crumbed chicken style patties, and the bacon style rasher, which all had extruded plant-proteins (TVP, pea, hemp, wheat, soy) as their main ingredient. Interestingly, previous literature has suggested that the use of extruded proteins is perceived as ‘unnatural’ (Michel et al., 2021a; Varela et al., 2022) and is a barrier for PBMA product choice (Onwezen et al., 2021). Consumers in the current study were not informed of the sample ingredients and so although the sensory experience of these products is acceptable, concern for level of processing may be a subsequent barrier to purchase for some consumers.

4.1. Effects of perceived similarity to meat on liking and emotional response

The finding that meat flavour was the strongest driver for liking is in agreement with previous sensory evaluations that characterised meat-like taste as an important predictor for product acceptance (Barker and McSweeney, 2022; Baune et al., 2023; Godschalk-Broers et al., 2022; Neville et al., 2017; Sogari et al., 2023) and an online survey which reported that consumers would like PBMA to have a stronger meat-taste and more meat-like texture than the options that are currently available (Wahrens et al., 2023). However, previous studies contained only individual product categories (e.g. all samples) or relatively low sample numbers. The current study adds to previous findings that meat flavour is an important driver for liking across the whole PBMA category, regardless of the product format, and presents evidence that A-NZ consumers overwhelmingly prefer meat-like PBMA over PBMA that are not perceived to be meat-like when both product sub-categories are compared. Consistently, meat-like samples were associated with positive emotions such as ‘curious’, ‘happy’, ‘pleasant’, and ‘satisfied’, whereas samples that were not perceived to be similar to meat were associated with negative emotion terms such as ‘disappointed’ and ‘dissatisfied’ – indicating that expectations for these samples were unmet. Failed expectations was reported by 35 % of consumers as a reason not to repurchase a PBMA after trying a product once or twice (Good Food Institute, 2023) and so has a large impact on market success.

In focus groups, consumers have previously indicated that they do not necessarily want PBMA to imitate meat (Collier et al., 2021; Kerlake et al., 2022), but the focus groups did not include product tasting of PBMA made from wholefoods. In the current study, PBMA made from wholefoods, and not perceived as similar to meat, did not meet the acceptance criteria consumers have for such products, highlighting a gap between consumer wants and the offer of products currently available. These products were associated with ‘vegetable’, ‘wheat’, and

‘legume’ flavours and ‘pastry/doughy’, ‘soft’, ‘sticky’, and ‘gluey/slimy’ textures. Unlike the associated flavour attributes, the texture attributes were identified as negative drivers for liking and provide a clear steer to industry to avoid such characteristics in future products.

Although dietary groups were not compared in the current study, it is acknowledged that meat consumption dietary preferences impact consumer expectations of a meat replacement. In focus groups with A-NZ (Kerlake et al., 2022) and Swedish (Collier et al., 2021) consumers, omnivores expressed that they were impressed with PBMA that closely resembled meat, whereas vegans and vegetarians felt meat substitutes that closely resembled meat were ‘too real’ or ‘strange’ such that it created negative experiences. However, when evaluated sensorily, vegans liked currently available PB chicken and beef alternatives more than flexitarians (Wahrens et al., 2023), and omnivores rated plant-based salami lower for ‘meat taste’ than flexitarians and meat-avoiders (Pointke et al., 2022). These findings suggest that while omnivores may have a higher preference for meat-like PBMA compared to meat avoiders, they may also be more demanding than consumers who reduce or eliminate their meat intake. This aligns with findings that meat avoiders and flexitarians have more positive perceptions of PBMA than omnivores in terms of taste, texture, effort to prepare, protein content, and environmental friendliness (Michel et al., 2021b). To achieve significant benefits to planetary and human health, consumption of meat and animal products would have to decrease drastically (Willett et al., 2019). Differences in perception of meat-like and vegetable-based PBMA between consumers with different diet preferences should be investigated in the future to investigate how consumers with different diets can optimally be engaged to participate in the transition towards more plant-based diets.

4.2. Sensory attributes contributing to perceived similarity to meat and sample acceptance

Most sensory variation between samples was attributed to meat-related versus vegetable-related sensory attributes highlighted by the first PC of both the PCAs conducted on all sensory attributes combined, and singularly on flavour and texture attributes. However, variation also occurred in attributes relating to the remaining PCs which were not characteristic properties contributing to PBMA similarity to meat. The attributes ‘fried’ appearance, flavour (fried breadcrumbs), and texture (crispy), were responsible for the second dimension of variance between all sensory attributes.

Sensory attributes such as ‘caramelised’ and ‘smoky/grilled’ flavours and ‘moist/juicy’ and ‘tender’ textures have previously been reported to be present in meat products (Adhikari et al., 2011; Hayes, 2008) and were, in addition to meat flavour itself, other drivers of liking in the current study. Crumbed/fried attributes were also identified as important drivers of liking. Importantly, crumbed/fried characteristics are not necessarily associated with meat products and therefore could potentially be used to increase consumer acceptance of products that do not aim to imitate meat products. Conversely, drivers of disliking – such as stale, bitter, gluey/slimy, and pasty/doughy – are sensory attributes that were previously identified in traditional PBMA (Kaczmarek et al., 2021) and were associated with disliked PBMA made from wholefoods in the current study.

Interestingly, differences in flavour profiles between different sample categories aiming to imitate meat were revealed. Beef style patties, sausages, and the bacon alternative – generally well-liked samples – were mostly associated with flavour terms such as ‘caramelised’, ‘moist/juicy’, ‘smoky/grilled’, and ‘savoury’. In contrast, chicken style pieces and beef style dices – generally less liked than the former categories – were associated with attributes including ‘flavourless’ and ‘cardboard/stale’. Moreover, the chicken style pieces and beef style dices are marketed as products that imitate chicken and beef respectively. However, they were not perceived to be particularly meat-like by the majority of participants, highlighting disparity between some product names and

consumer perception. It is relatively challenging to achieve the texture of specific cuts of meat in a PB product compared to the texture of a processed meat product such as a patty (Fiorentini et al., 2020) and so, not surprisingly, PB burger patties have a larger market share and growth (Good Food Institute, 2022). It is possible that meat pieces/chunks are relatively underdeveloped compared to PB burger patties and sausages, and this study's results suggest there are innovation opportunities to add flavour to this product category.

4.3. Emotional response was determined by perceived similarity to meat and flavour profile

Emotional response towards PBMA has scarcely been investigated. An online survey determined that emotions that participants anticipated whilst eating a plant-based burger patty were 'happy', 'satisfied', and 'relaxed' (Zandstra et al., 2024). In contrast, emotional response to blind tasting of a single plant-based burger patty was predominantly negative, where the most commonly cited terms were 'disappointed', 'discontented', and 'distrust' (Schouteten et al., 2016). This study adds to existing literature that a wide range of emotions are evoked by a range of products with different sensory characteristics within the PBMA category. Most of the variance between samples was attributed to the valence related emotions (i.e. positive vs. negative), relatively less by arousal level (i.e. active vs. passive), of emotions.

Furthermore, emotional response data revealed differences between samples that were similarly liked, especially for the samples that were perceived to be 'somewhat similar to meat'. Whereas most of the variance between samples was caused by the valence of emotions, separating samples perceived to be similar to meat from those that were not, samples that were 'somewhat similar to meat' were spread around the biplot indicating that they evoked both positive and negative emotions, depending on the sample. For example, despite the finding that samples 'somewhat similar to meat' were similarly liked on average, chicken style pieces were associated with 'calm' and 'neutral', whereas beef style dices were associated with 'anxious' and 'suspicious'.

The level of emotional activation was likely dependent on sensory experience as samples associated with intense flavours such as saltiness or hot spices were associated with activated terms ('adventurous', 'energetic'), whereas the well-liked samples that were associated with more deactivated terms ('calm', 'pleasant') were not associated with any intense flavours – except meat flavour. For samples associated with negative emotional terms, samples associated with deactivated emotional terms ('bored', 'neutral', 'disappointed') tended to have a lack of flavour, or were associated with vegetable-related flavours. Activated negative terms ('suspicious', 'disgusted', 'unhappy') were mostly related to textural terms ('pasty/doughy', 'soft', 'gluey/slimy', 'sticky'), suggesting that inferior textures evoke stronger negative emotions than the flavours related to wholefood ingredient PBMA.

4.4. Limitations and future research

This is the first study to characterise a wide range of different PBMA, including multiple product types and products that were and were not perceived to be similar to meat, for consumer acceptance, sensory characteristics, and emotional response. However, several limitations to the research can be acknowledged. First, the results are specific to samples available in A-NZ (and A-NZ consumers), which may be a relatively immature PBMA market (FoodHQ, 2021). Secondly, this study was advertised as a 'plant-based meat alternative study' and participants may have expected to be exposed to products that aimed to imitate meat-like characteristics. This could have affected sample evaluation (Caputo et al., 2022; Collier et al., 2021; Grasso et al., 2022; Schouteten et al., 2016) – especially if the samples did not meet participant expectations. Thirdly, products were tested alone but in reality are likely to be consumed within the context of a meal, which is likely to affect the acceptance (Cordelle et al., 2022) and perception of sensory attributes

(Gonzalez-Estanol et al., 2023). Lastly, the participant sample was overrepresented by female participants. Future research should investigate how the addition of other accompanying foods affect consumer experience/acceptance, particularly as regards the generally less-liked vegetable-based products compared to the relatively well-liked 'meat-like' products. Lastly, it is relevant to explore the impact of diet (vegan/flexitarian/omnivore), personality characteristics and values concerning health, sustainability and animal welfare on sample expectation and evaluation, to generate deeper insights into the effects of consumer characteristics on PBMA acceptance.

5. Conclusions

In summary, a wide variety in product acceptability was presented across a sample set representing the range of PBMA products available in market, which varied considerably in their sensory profile and perceived likeness to conventional meat. Flavour liking emerged as the most important modality for overall liking of a product, followed by texture liking, and to a lesser extent by liking of appearance. Sensorially, samples differed mostly based on their similarity to meat, compared to wholefood-related flavours and textures. Products that were perceived to be similar to meat received the highest ratings of acceptance and were associated with positive emotional response. In contrast, PBMA made from wholefoods were associated with negative drivers for liking, such as 'gluey/slimy' and 'pasty/doughy'. Products made from wholefoods do not currently meet consumer needs and are a target area for product development and optimisation. Overall, PBMA with meat-like characteristics are currently preferred by consumers, validating the ongoing industry focus on improving the meat-like properties of PBMA products; however, this study importantly provides key insights regarding product characteristics that could be pursued to improve those PBMA made from wholefoods that do not yet meet consumer requirements.

CRedit authorship contribution statement

Caroline Giezenaar: Conceptualisation, Research design, Ethics application, Data collection, Data analysis, Writing – original draft, Writing – review & editing. **Rebekah E Orr:** Research design, Data analysis, Writing – review & editing. **A. Jonathan R. Godfrey:** Conceptualisation, Research design, Data analysis, Writing – review & editing. **Robyn Maggs:** Research design, Data collection. **Meika Foster:** Writing – review & editing. **Joanne Hort:** Conceptualisation, Research design, Funding acquisition, Supervision, Writing – review & editing. All authors approved the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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